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Calculation of Factors to Convert from Air Kerma to Absorbed Dose to Water for Medium Energy Photons

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R F Nutbrown and D R Shipley
Centre for Ionising Radiation Metrology
National Physical Laboratory
Queens Road
Teddington
Middlesex TW11 0LW
United Kingdom

Abstract. The IPEMB[1] code of practice for the determination of absorbed dose for X-rays below 300 kV generating potential is a dedicated dosimetry protocol for the determination of absorbed dose based on the air kerma evaluation method for medium energy X-rays. Three separate energy ranges are dealt with in the code of practice, however, this report is only attempting to reproduce the factors in one particular range (0.5 - 4.0 mm Cu HVL) for X-rays generated at 135 and 280 kV. These X-ray qualities are used in the NPL therapy level calibration service. This new method includes the use of an air kerma calibration factor, N_K, for the ionisation chamber, and the ratio of the mass-energy absorption coefficients of water to air and factors that account for the change in the response of a NE2561 ionisation chamber between calibration in air and measurement in a water phantom, k_{ch}, instead of the old F factor. This report describes the work that was undertaken to reproduce the product of the ratio of the mass-energy absorption coefficients of water to air and the k_{ch} factors. The majority of this work was carried out using Monte Carlo techniques based on the EGS4 code system.

The factors calculated in this report were found to agree with values quoted in the IPEMB code of practice to within 4.2%. The quoted uncertainty for this work is 1.4% and the uncertainties for the factors quoted in the IPEMB code of practice are 3%. Hence this is reasonable agreement. Possible discrepancies in the values may be due either to limitations in the EGS4 code system, simplifications made in the chamber geometry or on the reliance on experimental data which is not quite applicable to its' use in this work.

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

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1. Introduction

The National Physical Laboratory (NPL) provides a therapy level calibration service for low and medium energy X-rays. This service is based on a primary standard free air chamber, for the calibration of hospital secondary standard dosimeters in air, such as the NE2561 ionisation chamber, in terms of air kerma. Measured values of the chamber response at the reference depth in a water phantom can then be converted to absorbed dose using factors quoted in the IPEMB code of practice for the determination of absorbed dose for X-rays below 300 kV generating potential (0.035 mm Al - 4 mm Cu HVL; 10 - 300 kV generating potential)[1]. This code of practice is based on the air kerma determination method that uses an air kerma calibration factor for the ionisation chamber, the ratio of mass-energy absorption coefficients of water to air and k_{ch} values instead of the old F factor.

This report describes the work which was undertaken to reproduce the product of the ratio of the mass-energy absorption coefficients of water and air, and the corrections which are applied to the air kerma calibration factor to account for the change in the response of the ionisation chamber between calibration in-air and measurement in-phantom, k_{ch}. These factors were reproduced at X-ray qualities of 135 and 280 kV generating potential (0.50 and 4.0 mm Cu HVL). The majority of this work was carried out using Monte Carlo techniques based on the EGS4[i] code system. Section 2 of this report describes the two EGS4 user codes used in the simulation of a NE2561 chamber in a phantom, and their validation. An overview of the method that was used to reproduce values of the ratio of the mass-energy absorption coefficients of water and air and k_{ch} is given in Section 3. The uncertainties in the derived factors are discussed in Section 4 and these values are compared with those obtained from the code of practice in Section 5.

2. EGS4 and associated user codes

2.1 The EGS4 code system

Most of the calculations described in this report were carried out using the EGS4 code system with the PRESTA[ii] electron transport algorithm[2]. These codes form a general-purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies ranging from a few keV to several TeV. The package, used in conjunction with a user-written code, calculates the development of an electron-photon cascade from a single incident electron or photon, and transports each particle through the geometry until it reaches a predefined energy cut-off or discard boundary. Electron-photon transport can be simulated in any of 100 elements or mixture of these elements, or any compound. The associated package PEGS4[iii], documented by Nelson et al[3], is used to generate data sets of the required materials for subsequent use by EGS4.

2.2 Description of user codes

This section describes the following two EGS4 user codes used in this work and their validation. Energy spectra are used as input by the code PHSCHAM to score phase space information on the surface of a thimble shaped volume at depth in a phantom. This phase space information is subsequently used by the dose scoring code DOSCHAM. Both of the codes have been developed at

i Electron - Gamma Shower version 4
ii Parameter Reduced Electron - Step Transport Algorithm
iii Pre-processor for EGS4

NPL and are at present prototype versions for NPLEGS[iv].

The EGS4 user code PHSCHAM (NPLEGS Prototype Version 1.10) uses as input the energy spectra from a point source to simulate the passage of electrons and photons through a cubic phantom. The angular information was obtained by representing the X-ray tube as a point source at 75 cm from the front face of the phantom with a specified beam radius on the front face. The code then stored the full phase space information (i.e. position, direction cosines, charge and weight), the source particle number and an appropriate random number seed of each particle striking a specified thimble shaped volume (i.e. a cylinder with a hemisphere at one end) at a particular depth in the phantom. The source particle number is the record number of the particle in the incident phase space file. The particle number that has been assigned by PHSCHAM is then used as a tag by DOSCHAM to ensure that in subsequent dose calculations a particle and all its progeny are placed in the same statistical bin. The random number seed that is used by DOSCHAM is derived from the seeds of the RANMAR[v] random number generator used in PHSCHAM.

Another EGS4 user code DOSCHAM (NPLEGS Prototype Version 1.30) was used to read in the phase space information generated by the user code PHSCHAM to calculate the dose deposited to the internal regions of the thimble shaped geometry representing a NE2561 ionisation chamber. The thimble shaped volume has an internal structure that is made up of a series of cylinders, slabs and hemispheres. The code divides each dose calculation into 20 independent statistical bins from which the mean dose and standard error are determined. DOSCHAM uses a generic 32 bit random number generator[vi] with the random number seed stored in the phase space file to initialise each particle.

PHSCHAM and DOSCHAM have been validated previously at higher photon energies between ^{60}Co and 19 MV for a NE2561 chamber in a water phantom[4] using calculated fluence spectra as input. This work also validated PHSCHAM and DOSCHAM for a NE2561 chamber in air in 2 MV photons using the point source option within PHSCHAM.

For this work, an option to allow the use of the variance reduction technique Russian Roulette[5] has been developed for use in DOSCHAM simulations. This allows for a proportion of photons to be discarded on leaving the chamber geometry and weighting the remaining photons accordingly. For example, if the Russian Roulette cut-off, RRCUT, is set to 0.1, 90% of all photons are discarded and the remaining 10% are retained with their weighting scaled by 1/RRCUT (in this case this is a factor of 10). Providing that only a small number of photons which leave the chamber geometry scatter back, the simulation time required to obtain a given uncertainty in the dose will be greatly reduced. If a photon re-enters the chamber geometry it will have a weighting that has been increased by the Russian Roulette technique which is related to the proportion of photons which are discarded during the process. If this photon (and subsequent electrons) then contributes to the dose in the chamber, the uncertainty on the dose may significantly increase. The greater the weighting of the particle, the more the uncertainty on the dose will increase. Therefore there is an optimum value for the proportion of photons to be discarded. The Russian Roulette option has been validated by comparing chamber results for calculations with and without this option for a NE2561 chamber in a water phantom in photons

iv Extensions to the EGS4 system in the form of user-codes, PEGS4 data sets and other enhancements developed at NPL

v RANMAR is a "Fibonacci Method" pseudo random number generator devised by Marsaglia and Zeman

vi The generic 32 bit random number generator distributed with the original VAX version of EGS4 was used here

with a generating potential of 280 kV. There was found to be a difference in the absolute dose results of 0.4% where the uncertainties on the dose calculations were of the order 0.4% (at 1σ), i.e. no significant difference at the 0.4% level.

For a given simulation DOSCHAM over-samples a finite list of particles that has been stored on the surface of the thimble shaped volume. As this list only contains particles that are likely to strike the volume of interest, CPU time is not wasted simulating particles that are not likely to contribute to the dose in the cavity. Over-sampling the particles on the list but with different initial random number seeds also reduces the CPU time required for a given PHSCHAM simulation. Therefore there is a reduction in the total amount of CPU time a simulation will take before a given uncertainty in the dose is reached. The calculations documented in this report require the ratio of doses from two similar simulations that use the same phase space information. By initialising the particles in the list with the same random number seed in corresponding dose calculations the particle transport and hence the calculated dose values should be more closely correlated.

For all EGS4 calculations the material information is read in from data sets generated using PEGS4. These data sets contain information on all the materials used including their density, composition and electron and photon cross sections over a selected energy range. The particle transport parameters AE[vii], UE[viii], AP[ix] and UP[x] are set within the PEGS4 input files that are used to create the data sets.

3. Calculation of the absorbed dose calibration factors

3.1 Overview

This section will look at the method by which values of the product of the mass-energy absorption coefficients of water and air and the factors that are applied to the air kerma calibration factor, to account for the change in response between calibration in air and measurement in a water phantom, k_{ch}, are calculated. This report is only interested in reproducing values for medium energy X-rays, i.e. X-rays of half value layers in the range 0.5 - 4 mm Cu (or equivalently above 8 mm Al) covering approximately those qualities which are generated at tube voltages in the range 160 - 300 kV.

3.1.1 Overview of the IPEMB code of practice

The IPEMB code recommends that the absorbed dose is determined at a fixed reference depth of 2 cm which, for a given fixed field size, is given by:

$$D_{w,z=2} = M_w \cdot N_K \cdot k_{ch} \cdot \left[\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=2,\phi} \qquad (3.1)$$

Where:

$D_{w,z=2}$ is the dose to water in grays at the position of the chamber centre at a depth z = 2 cm when the chamber is replaced by water.

vii The minimum (total) electron energy required for explicit δ-ray production
viii The maximum (total) electron energy
ix The photon equivalent of AE
x The maximum photon energy

M_w is the chamber reading obtained at a depth of 2 cm in water, corrected to standard temperature and pressure (20°C, 1013.25 mbar and 50% relative humidity).

N_K is the chamber calibration factor in grays per scale reading to convert the instrument reading at the beam quality (HVL) concerned to air kerma at the reference point of the chamber with the chamber assembly replaced by air.

k_{ch} is a factor which accounts for the change in the response of the ionisation chamber in air and measurement in a phantom.

$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w/air}\right]_{z=2,\phi}$ is the mass-energy absorption coefficient ratio, water to air, averaged over the photon spectrum at 2 cm depth in water and field diameter ϕ.

By definition the chamber calibration factor in grays per scale reading to convert the instrument reading at the beam quality (HVL) concerned to absorbed dose in water at the position of the chamber centre with the chamber assembly replaced by water, N_w, is given by:

$$N_w = \frac{D_{w,z=2}}{M_w} \tag{3.2}$$

Similarly, by definition, the chamber calibration factor in grays per scale reading to convert the instrument reading at the beam quality (HVL) concerned to air kerma at the reference point of the chamber with the chamber assembly replaced by air, N_K, is given by:

$$N_K = \frac{K_{air}}{M_{air}} \tag{3.3}$$

Where:

K_{air} is the air kerma at the reference point of the chamber.

M_{air} is the chamber reading obtained in air, corrected to standard temperature and pressure.

Under conditions of charged particle equilibrium, as for this situation, K_{air} is given by:

$$K_{air} = D_{air}\left(1 + \left(K_r / K_c\right)_{air}\right) \tag{3.4}$$

Where:

D_{air} is the dose to the air in grays at the reference point of the chamber.

$\left(K_r\right)_{air}$ is the radiative air kerma at the reference point of the chamber.

$\left(K_c\right)_{air}$ is the collision air kerma at the reference point of the chamber.

For low Z materials such as carbon, water and air at the energies under consideration for this work the contribution of the radiative air kerma to the total air kerma will be negligible (i.e. losses to bremsstrahlung radiation are < 0.1%) and so:

$$K_{air} = D_{air} \tag{3.5}$$

And so Equation 3.3 becomes:

$$N_K = \frac{D_{air}}{M_{air}} \tag{3.6}$$

Therefore, by combining equations (3.1), (3.2) and (3.6) the following may be derived:

$$\frac{D_{w,z=2}}{D_{air}} = \frac{M_w}{M_{air}} \cdot \frac{N_w}{N_K} = \frac{M_w}{M_{air}} \cdot k_{ch} \cdot \left[\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=2,\phi} \tag{3.7}$$

Where the factor, k_{ch}, can be defined as[6]:

$$k_{ch} = k_{\alpha} \cdot k_{st} \cdot p_{rep} \cdot k_{sleeve} \tag{3.8}$$

Where:

k_{α} allows for the energy and angular dependence on the response of the ionisation chamber in the water phantom compared to when the chamber is calibrated in air.

k_{st} accounts for the influence of the stem on the response of the ionisation chamber free in air and in water.

p_{rep} is the replacement correction which accounts for the effective point of measurement being displaced due to the change of medium within the chamber cavity and change in attenuation and scatter of the beam.

k_{sleeve} accounts for the effect of the waterproof sleeve on the response of the ionisation chamber in water.

3.1.2 Overview of the simulations

The simulations carried out in this work (see Section 3.4) to determine the dose to the cavity of the NE2561 ionisation chamber in a water phantom modelled the chamber explicitly except with only 1 mm of stem. The rest of the stem was not included and so a stem correction, $k_{st,w}$, is necessary to account for the lack of a chamber stem in the water phantom calculations. In order to minimise step size dependencies in the dose ratio, simulations to determine the dose to water at the reference depth in the water phantom model a NE2561 ionisation chamber with all materials replaced with water of the same density as the original material instead of normal density water (water equivalent chamber). The simulations of the water equivalent chamber require a correction to account for the effective point of measurement being displaced due to the change of medium within the chamber cavity and change in attenuation and scatter of the beam. In this work the replacement correction, p'_{rep}, is therefore defined as the ratio of the chamber response when all materials have been replaced with normal density water

to the response of the water equivalent chamber for a stemless chamber.

N_w can therefore be given by:

$$N_w = \frac{D_{WE} \cdot p'_{rep}}{D_{ch,w} \cdot k_{st,w}} \tag{3.9}$$

Where:

D_{WE} is the dose to the cavity of the water equivalent stemless chamber in grays at the position of the chamber centre.

$D_{ch,w}$ is the dose to the cavity of the stemless chamber in water in grays at the chamber centre.

The stem correction in water, $k_{st,w}$, can be expressed as:

$$k_{st,w} = k_{st.scat,w} \cdot k_{st.rep,w} \tag{3.10}$$

Where:

$k_{st.scat,w}$ is the stem scatter correction in water.

$k_{st.rep,w}$ is the stem replacement correction in water.

The simulations to determine the dose to the cavity of the NE2561 ionisation chamber in air also modelled the chamber explicitly but with only 1 mm of stem. The rest of the stem was not included and so a stem correction, $k_{st,air}$, is also required, as before. Simulations to determine the dose to air at the position of the chamber centre, model a NE2561 ionisation chamber with all materials replaced with air of the same density as the original material instead of normal density air (air equivalent chamber). Again, this is in order to reduce step size dependencies in the dose ratio. The primary dose component excluding primary photon attenuation is of interest for this calculation as any effects due to scatter and attenuation in the dense air wall surrounding the cavity are not included in this component. This means that a replacement correction, which would account for the effective point of measurement being displaced due to the change of medium within the chamber cavity and change in attenuation and scatter of the beam, is not required.

N_K can therefore be given by:

$$N_K = \frac{D_{AE}}{D_{ch,air} \cdot k_{st,air}} \tag{3.11}$$

Where:

D_{AE} is the dose to the cavity of the air equivalent chamber in grays at the position of the chamber centre.

$D_{ch,air}$ is the dose to the cavity of the chamber in air in grays at the chamber centre.

The stem correction in air, $k_{st,air}$, is wholly due to stem scatter with no stem replacement correction

required, and so:

$$k_{st,air} = k_{st.scat,air} \tag{3.12}$$

Where:

$k_{st.scat,air}$ is the stem scatter correction in air.

Both in water and air, the stem tends to increase the response of the chamber, $D_{ch,air}$, due to scatter from the stem, therefore, the stem scatter corrections, $k_{st.scat,w}$ and $k_{st.scat,air}$ are less than unity. In water, the replacement of the water by the stem tends to reduce the response of the chamber, $D_{ch,w}$; therefore, the stem replacement correction $k_{st.rep,w}$ is greater than unity. For this work the stem scatter corrections in both water and air, $k_{st.scat,w}$ and $k_{st.scat,air}$, have been taken to be the same; this is valid when the field size and spectra are the same in-air and in-phantom (see section 3.6.1 of Reference 6). The stem replacement corrections for a NE2561 ionisation chamber irradiated in a 11.3 cm diameter field are taken from Figure 3.7a of Reference 7. Chamber replacement corrections for the same chamber in water irradiated with a 10 x 10 cm field are taken from Reference 7, and are assumed to be equivalent to the replacement correction p'_{rep} used here.

3.1.3 Summary

Hence, combining Equations (3.7), (3.9), (3.11) and (3.12) gives:

$$\frac{N_w}{N_K} = \frac{D_{WE}}{D_{ch,w}} \cdot \frac{D_{ch,air}}{D_{AE}} \cdot \frac{p'_{rep}}{k_{strep,w}} = k_{ch} \cdot \left[\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=2,\phi} \tag{3.13}$$

This expression can then be used to determine the product of the ratio of the mass-energy absorption coefficients of water and air and the chamber factor k_{ch}.

3.2 Simulation Geometry

Nominal dimensions for the simulation geometry of the NE2561 ion chamber were used for these calculations. See Appendix 1 for the material specifications used. The specification of Baltic amber was used for amber, although ideally, the composition of the amber pellets used in the manufacture of NE2561 chambers should have been determined and used instead; see Section 4 for an estimate of the associated uncertainty. For both the in-phantom and in-air calculations the chamber was modelled at a distance of 77 cm from the source. The standard therapy level calibration distance is 75 cm but at these energies the effect of using slightly different distances will be negligible. For the in-phantom simulations the chamber was modelled at the same depth in water as is quoted in the IPEMB code of practice. For medium energy X-rays this depth is 2 cm within a 30 cm cubic water phantom.

The NE2561 chamber simulation geometry matches the actual construction quite closely. The only major difference that may affect the calculated dose values is that only 1 mm of chamber stem material adjacent to the air cavity has been modelled (which is sufficient for charged particle equilibrium in the chamber cavity). This means that the surface area of the scoring volume is as close to the dose scoring regions as possible in order to maximise the correlation in the dose calculations using the same phase

space information on the surface. All differences in the internal structure of the simulation geometry are minor. However, at these energies the response of a NE2561 chamber depends quite significantly on the assembly and construction. As all the dimensions quoted are nominal this is an uncertainty that is inherent in the calculations.

3.3 PEGS4 Data sets

The values of AE and AP were set to 0.521 MeV and 0.010 MeV respectively for all materials except for the air inside the cavity of the NE2561 ion chamber, the graphite wall, the Perspex sheath and the water and air regions surrounding the chamber. AE and AP were set to 0.516 MeV and 0.005 MeV for the air inside the chamber cavity and 0.800 MeV and 0.010 MeV for the Perspex, water and air regions surrounding the chamber. The graphite wall of the chamber was divided into three regions each with different values of AE but with the same value of AP of 0.010 MeV. The value of AE was set to 0.521 MeV within the inner 0.03 mm of the graphite wall, to 0.561 MeV within the next 0.13 mm and to 0.635 MeV within the final 0.34 mm. UE and UP were set to 20.511 MeV and 20.0 MeV for all materials.

The IAPRIM[8] and EPSTFL[9] options that are set within the PEGS4 input files were used. The IAPRIM option normalises the bremsstrahlung cross-sections so that PEGS4 gives the same radiative stopping power for electrons as given in ICRU Report 37[10]. The EPSTFL option allows the user to input an arbitrary density-effect correction for use in calculating electron and positron collision stopping powers. The density effect corrections were obtained using the program EPSTAR[xi] (S.M. Seltzer - version 2.0B). These values were then used in conjunction with the PEGS4 input files to create the material data sets.

For the simulations calculating the response of the water or air equivalent chamber the materials specified used the density effect corrections for normal density water or air. In the case of the water equivalent chamber this is because the replacement correction, which is required to account for the differences between a water equivalent chamber and replacing the chamber with normal density water corrects for the density and not the properties of the media. This is similarly true for the air-equivalent case except, as the primary dose component excluding primary photon attenuation has been used in determining the value of N_w, no replacement correction is required

3.4 Method of Calculation

The air kerma and absorbed dose calibration factors for a NE2561 ion chamber were determined under standard therapy level calibration conditions in X-rays with generating potentials of 135 kV and 280 kV. X-ray spectra for the two qualities of interest have been measured using an intrinsic germanium detector[11]. The calibration factors were determined by calculating the dose to the sensitive volume when all materials are present and when all the chamber materials have been replaced with water or air of the same density (i.e. a water or air equivalent chamber).

The EGS4 user code PHSCHAM used the measured energy spectra (read in from a file) as input to calculate the full phase space spectra incident on the surface of the stemless chamber both within a water phantom and in air. In all cases the X-ray tube was treated as a point source where the beam

[xi] Calculates stopping power (collisional, radiative and total), CSDA ranges, bremsstrahlung yield for electrons (or positrons) with kinetic energies from l keV to 10 GeV and the mean excitation energy of the material.

radius at the centre of the chamber was 5.58 cm in water and 3.50 cm in air. This is equivalent to 5.44 cm and 3.41 cm respectively at the front face of the phantom. For each X-ray quality in-phantom and in-air two dose calculations were carried out with DOSCHAM using as input the full phase space information generated by PHSCHAM.

For the in-phantom situation the first calculation determined the dose scored to the air cavity of the ion chamber (plus waterproof perspex sheath) in a water phantom. The second calculation was identical except that all the chamber materials were replaced with water of the same density as the original material, (a water equivalent chamber). For the in-air situation the first calculation determined the dose scored to the air cavity of the ion chamber in air. The second calculation was identical except that all the chamber materials were replaced with air of the same density as the original material, (an air equivalent chamber). DOSCHAM has an option to allow the primary dose, the primary dose excluding primary photon attenuation and the scattered dose to be scored separately as well as the total dose. When determining the dose at a point in air in the absence of the chamber, D_{air}, the primary dose component excluding primary photon attenuation is used.

The EGS4 transport parameters, ECUT[xii] and PCUT[xiii], were set to 0.521 MeV and 0.005 MeV for all regions in the geometry except for the air cavity inside the NE2561 ion chamber, the phantom region outside the chamber geometry, the perspex sheath and the graphite wall. For the air cavity region inside the chamber ECUT was set to 0.516 MeV and PCUT was set to 0.001 MeV. For the phantom region outside the chamber (for both the in-air and in-phantom cases) and the perspex sheath ECUT was set to 0.800 MeV and PCUT was set to 0.005 MeV. The graphite wall of the chamber was divided into three regions each with a different value of ECUT but with the same value for PCUT of 0.005 MeV. The value of ECUT was set to 0.521 MeV within the inner 0.03 mm of the graphite wall, to 0.561 MeV within the next 0.13 mm and to 0.635 MeV within the outer 0.34 mm. Since the current version of EGS4 only allows a global ECUT to be set the AE values for the materials in each region were used to force up the value of ECUT to the required value greatly improving the efficiency of the chamber calculations. ESTEPE[xiv] was set to 2% for all calculations. Calculations were performed to find the optimum value for RRCUT. A value of 0.1 was used in all dose calculations.

4. Uncertainties

There are a number of non-random uncertainties that are present in the values for factors derived in this work. It is therefore necessary to understand the nature of these uncertainties and to make an estimate of their size. This section will consider the uncertainties present in the EGS4 calculations and in the corrections derived for this work. Overall estimates of these uncertainties are given in Table 4.1.

xii The cut-off (total) energy for charged particle transport

xiii The cut-off energy for photon transport

xiv Maximum fractional energy loss per step due to the continuous slowing down of charged particles

(All % standard uncertainties)	Type A (random)	Type B (non-random)
$D_{WE}/D_{ch,w}$	0.71	0.52
$D_{AE}/D_{ch,air}$	0.71	0.52
$k_{st.rep,w}$	-	0.5
p'_{rep}	-	0.4
Total	1.00	0.98
Overall	1.4	

Table 4.1: - Table of Uncertainties

Errors in the transport physics within EGS4 still exist due to the many approximations that are determined by the choice of ESTEPE, b_{min}[xv] and any transport parameters. By keeping the density of the water or air the same as the materials in the normal density chamber calculation and matching simulation geometries the electron transport within the two simulations is more closely matched. Therefore, by keeping the electron transport similar in the two calculations, many of the non-random uncertainties introduced by these approximations that are present when performing ion chamber simulations are reduced when taking dose ratios. This method has been successful at higher energies, however, at these energies the chamber is fully built up so there is likely to be less correlation in the electron tracks inside the chamber. An uncertainty of 0.5% is considered appropriate for these effects.

Calculations have been made previously[4] to investigate for any dependence in the response of the ion chamber and water equivalent chamber on b_{min} or ESTEPE at higher energies. It was found that the absolute dose calculations did depend on b_{min} and ESTEPE. When values for b_{min} and ESTEPE were kept the same these uncertainties were significantly reduced when taking the dose ratio, as no significant dependence within the obtained random uncertainty was apparent. At the lower energies such as ^{60}Co there was found to be a possible dependence with ESTEPE in the dose ratio. In this case a reduced ESTEPE of 4% was used. For the calculations presented in this report an ESTEPE of 2% is considered adequate. Errors may also be introduced due to the uncertainty on the cross sectional data used in EGS4. However these effects are again reduced when taking ratios of doses as they will mostly cancel. Therefore an uncertainty of 0.1% (at 1σ) is considered pessimistic.

As mentioned in Section 3.2, there are minor differences in the geometry and materials that may affect the calculated response of the chamber at these energies. For example, the material specification for amber was taken to be that of Baltic amber when ideally the actual composition of the amber pellets should be used. A total uncertainty of 0.1% (at 1σ) for these effects is considered pessimistic. Therefore an overall non-random uncertainty of 0.52% (at 1σ) on the dose ratios taken in quadrature with the calculated random uncertainty is considered pessimistic where the total random uncertainty on

xv A parameter used by PRESTA to restrict the minimum electron step size near a boundary

the dose ratios is at most 0.71% (at 1σ).

Values of the stem replacement correction are taken from a best fit to measured[6] and calculated[7] values where the greatest spread between the line of best fit and any one point is 0.4%. Another possible source of uncertainty within the determination of the stem correction is that, as stated in Section 3.1.2, the stem scatter effects in-air and in-phantom are assumed to be the same for identical field sizes and spectra. For these calculations, the radius of the beam at the position of the chamber is 3.50 cm in air and 5.58 cm in water, however, effects due to the size of the beam should be negligible as long as the beam covers the full extent of the chamber, as is the case for the calculations presented in this report. Therefore an overall non-random uncertainty in the stem replacement correction of 0.5% is considered pessimistic. The non-random uncertainty in the replacement correction for a stemless chamber has been estimated to be of the order 0.2%. However, the use of this correction is not entirely applicable to this work. Therefore an overall non-random uncertainty in the replacement correction of 0.4% is considered pessimistic. Therefore, the total uncertainty in the ratio of calibration factors for water to air, N_w/N_K, is 1.4% (at 1σ).

5. Results and Discussion

Values for the chamber factor, k_{ch}, and the ratio of the mean mass-energy absorption coefficient, water to air, $\left[(\bar{\mu}_{en}/\rho)_{w/air}\right]_{z=2,\phi}$, which are given in Table 5.1, are taken from the IPEMB code of practice for medium energy X-rays. The quoted uncertainty in k_{ch} is $\pm 3\%$ (at 1σ) and the uncertainty in $\left[(\bar{\mu}_{en}/\rho)_{w/air}\right]_{z=2,\phi}$ is less than 1% (at 1σ). These uncertainties, when combined in quadrature, give an overall uncertainty of 3.2% (at 1σ). Values given in Table 5.2 for the stem replacement correction in water, $k_{st.rep,w}$, are taken from Figure 3.8 given in Reference 6 and values for the replacement correction in water, p'_{rep}, are taken from Reference 7.

	Generating Potential (HVL)	
	135 kV (0.5mm Cu)	280 kV (4.0mm Cu)
k_{ch} for ϕ = 11.16 cm	1.023	1.018
$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w/air}\right]_{z=2,\phi}$	1.041	1.102
$\frac{N_w}{N_K} = k_{ch} \cdot \left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w/air}\right]_{z=2,\phi}$	1.065	1.122

Table 5.1: - Values of N_w/N_K determined using factors from IPEMB code of practice

	Generating Potential (HVL)	
	135 kV (0.5mm Cu)	280 kV (4.0mm Cu)
$\frac{D_{WE}}{D_{ch,w}}$	1.0992	1.1148
$\frac{D_{AE}}{D_{ch,air}}$	1.0156	1.0128
$k_{st.rep,w}$	1.0325	1.012
p'_{rep}	0.986	0.990
$\frac{N_w}{N_K} = \frac{D_{WE}}{D_{ch,w}} \cdot \frac{D_{ch,air}}{D_{AE}} \cdot \frac{p'_{rep}}{k_{st.rep,w}}$	1.034	1.077

Table 5.2: - Values of N_w/N_K determined using Monte Carlo and empirical techniques

The values of N_w/N_K calculated in this report are lower than values determined using factors quoted in the IPEMB code of practice for medium energy X-rays by 3.0% at 135 kV and by 4.2% at 280 kV. The uncertainties on values in the IPEMB code of practice are of the order 3.2% and the total uncertainty in the values given in Table 5.2 is of the order 1.4%, therefore the results are in reasonable agreement to within 1-2σ.

6. Conclusions

Reasonable agreement between the IPEMB code of practice and calculation has been obtained within the large uncertainties. Any discrepancies are most likely caused by transport routines within EGS4, the reliance on empirical or other calculated data and also the large uncertainties on the IPEMB values. The electron transport physics within the current EGS4 user codes is not yet good enough for these types of applications; however, it may be possible to improve the agreement with the new electron transport routines in EGSnrc. These new routines will also make it possible to calculate N_w and N_K directly without the need to resort to new techniques to reduce non-random uncertainties in the current code (e.g. matched geometries) and the reliance on empirical or calculated data.

7. References

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Appendix 1: Material Specifications

The following is a list of all the materials used, their density and the percentage by weight of their constituents.

Material	Density (g/cm^{-3})	Constituent	Weight %
Aluminium	2.669	Al	100.0
Aluminium Alloy	2.669	Si	1.0
		Fe	0.5
		Cu	0.1
		Mn	0.3
		Mg	0.9
		Cr	0.2
		Zn	0.2
		Ti	0.1
		Al	96.7
Graphite	1.8	C	100.0
Amber	1.07	C	79.0
		H	10.5
		O	10.5
Air	1.205e-3	N	78.03
		O	21.03
		Ar	0.94
Water	1.0	H_2O	100.0
Perspex	1.19	$C_5H_8O_2$	100.0
Delrin	1.4	CH_2O	100.0

Table A1: Material specifications for all materials used in the simulations